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Experimental characterization of the mechanical behavior of two solder alloys for high temperature power electronics applications

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ABSTRACT

An experimental investigation of two potential candidate materials for the diamond die attachment is presented in this framework. These efforts are motivated by the need of developing a power electronic packaging for the diamond chip. The performance of the designed packaging relies particularly on the specific choice of the solder alloys for the die/substrate junction. To implement a high temperature junction, AuGe and AlSi eutectic alloys were chosen as die attachment and characterized experimentally. The choice of the AlSi alloy is motivated by its high melting temperature T_m (577 °C), its practical elaboration process and the restrictions of hazardous substances (RoHS) inter alia. The AuGe eutectic solder alloy has a melting temperature (356 °C) and it is investigated here for comparison purposes with AlSi. The paper presents experimental results such as SEM observations of failure facies which are obtained from mechanical shear as well as cyclic nano-indentation results for the mechanical hardening/softening evaluation under cyclic loading paths.

1. Introduction

Nowadays, high-temperature power electronics packaging designed for the power electronics systems are paramount components of the electrical inverters in the hybrid electrical vehicles as well as the aeronautical and military engines. Mainly, a power electronic packaging is subjected to a high thermomechanical and power cycling as well as external environmental conditions such as moisture and corrosion. At the end of the packaging lifetime, the failure happens very often due to the voids growth and microcracks propagation in the solder alloy. The last constitutes the major cause of the lifetime reduction. To take up the wide temperature ranges and the high current densities, a new high temperature packaging generation is currently investigated. In power electronic applications, diamond based semi-conductors appear to be the solution in order to widely increase the capabilities of the power electronic converters [1]. Diamond is known to have exceptional thermal, electrical and mechanical properties. In order to make use of the exceptional characteristics of the diamond and increase the packaging reliability at high temperatures, a good choice of the die attachment is primordial to improve the thermomechanical behavior of the electronic device. Many technologies have been proposed in the literature [4,5]. The first technology is concerning solders with a high melting temperature. Inspite of the availability of high temperature solders in power electronics, researches involving this kind of materials are scarce. The implementation cost of these alloys remains the major obstacle to their use. It should be also denoted that most solders which operate at temperatures higher than 500 °C are ternary alloys that may potentially cause the formation of unfavorable intermetallic phases in the interfaces. But this was not the rule. For example, studies were conducted on some ternary alloys such as the ternary systems AuAgGe and AgCuSb. It has been shown that for an AgCuSb system, the wettability, the temperature melting, the quality of the interface as well as the microstructure, are favorable for operating between 400 °C and 500 °C. This system is also compatible with a Ni/Au metallization deposited on an AlSiC substrate. No cracks or brittle intermetallic phases are formed [15]. However, Sb is an element classified as toxic although it is not affected by the RoHS and WEEE directives. Works are underway to test AuAgSi alloy with the same kind of metallization [11].

A second technology proposed to solve the problem of solder fatigue is to replace soldering by another technique compatible with the power module service conditions. This is achieved by replacing the junction chip/substrate and wire bonding connection by a low temperature sintering technique involving more resistant materials and thereby, minimizes the residual stresses produced at the elaboration process. Sintering consists on a powder form alloy which is subjected to a thermomechanical process (temperature

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Table 1
Die attachment techniques for high temperature electronic applications [3,4,7,8,10,12,17,19].

	T_m (°C)	CTE (ppm/K)	Young's modulus E (GPa)	Thermal conductivity λ (W/m K)	Elect. conductivity (10^7 S/m)
80Au20Sn [10]	280	16	68	58	63
88Au12Ge [12]	356	12	80	52	–
88Al12Si [7,19]	577	22–23	70	121	32
Au/In [4]	454	–	–	–	–
Au/Sn [11]	532	–	–	–	–
Ag/Cu [3]	780				
Ag/In [17]	850	–	–	–	–
Ag nanopowder [8,12]	961	19	9	240	41

and pressure) to achieve cohesion and densification of the particles at a temperature below the melting temperature of the basic components. Sintering additives are used to promote the process. In the electronic field, the most commonly used material is the powder of silver nanoparticles [2]. In this case, the resistance to active cycling can be greatly increased and a lifetime improvement of the electronic component can be obtained [6]. The major drawback of this technique is the relatively high sintering pressure able to cause premature cracks in the brittle module components especially in the silicon chips. There is also a challenge in the fixation and the alignment of the components before the pressure application. This innovative technique is already applied in industrial products [9,18].

Another prospective for joining is the exploitation of the diffusion mechanisms to produce a high temperature resistant bond at low temperatures [5]. The concept consists on assembling two parts with a low temperature melting metal, then performing a heat treatment to allow diffusion of the metal in solid or liquid phase to the substrates. The resulting bond has a melting temperature higher than the heat treatment temperature. Among the possible junctions obtained using this technique, we find the junctions formed by the Au/In multilayer (resistant binary alloy) [4], Ag/In and Ag/Sn (silver-rich solid phase), Cu/Sn (copper-rich solid phase) and especially Au/Sn (gold-rich solid phase). For example, some studies lead to the achievement of a high strength junction between the metallization $NiSi_2$/Cr/NiCr/Au of a silicon carbide semiconductor and an AuSn alloy after annealing for 2000 h at 350 °C [11]. In fact, when Sn diffuses in the Au metallization, its percentage in Au is reduced which increase the melting temperature of the junction [3,20]. Particular attention was also devoted to the AuIn alloy with a highly adhering indium component having a melting temperature of 157 °C. The indium reflow is carried out at 200 °C followed by an annealing step at 400 °C to obtain an AuIn junction able to withstand temperatures up to 450 °C [4]. The economic constraints depending on the alloys cost and the elaboration process of the joints promote the use of indium with other metals such as copper or silver. In the case of Ag metallization, the procedure for obtaining a high temperature resistant junction with Ag

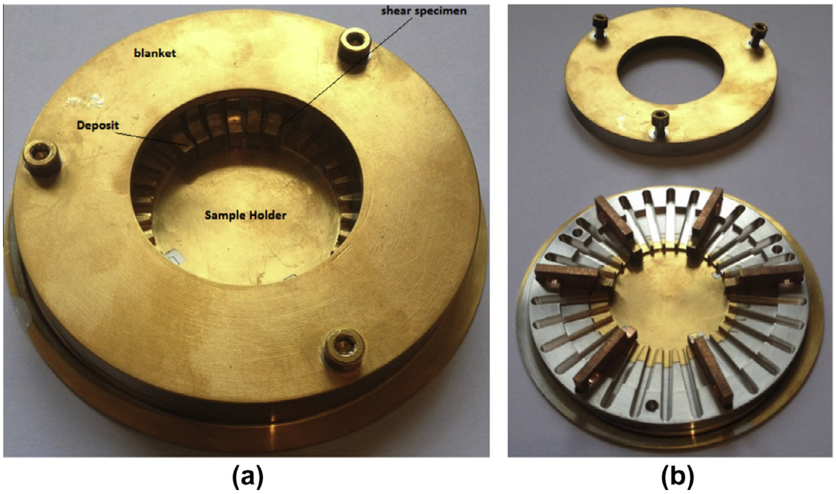

Fig. 1. Designed deposition tool for sputtering deposition. (a) Assembled and (b) decomposed.

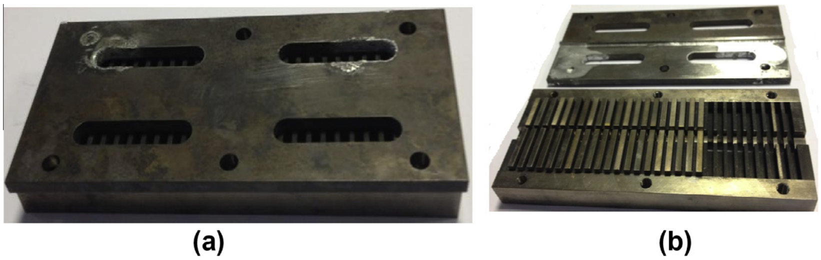

Fig. 2. Designed high temperature titanium tool for the reflow operations. (a) Assembled and (b) decomposed.